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Robot Manipulator Control and Computational Cost

Yehong Zhang
University of Pennsylvania

Richard P. Paul
University of Pennsylvania

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Abstract

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Comments

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**ROBOT MANIPULATOR
CONTROL AND COMPUTATIONAL
COST**

**Yehong Zhang
Richard P. Paul**

**MS-CIS-88-10
GRASP LAB 134**

**Department of Computer and Information Science
School of Engineering and Applied Science
University of Pennsylvania
Philadelphia, PA 19104**

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Yehong Zhang

Richard P. Paul

Computer and Information Science Department
University of Pennsylvania
Philadelphia, PA 19104

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In this paper robot control algorithms are considered from the point of view of computational complexity. All the algorithms provide for hybrid position and force control which is appropriate to unstructured environments. Both joint coordinate and generalized coordinate motion schemes are considered. The findings are interesting in that the peripheral processing involved in all methods, sometimes, swamps the orders of magnitude differences in computation involved in the inner loops. It is also interesting to note the similarity in complexity between direct methods and differential. Between joint coordinate methods and generalized coordinate methods there is a general two to one ratio in complexity. In general a 0.75 M Flop, 1.25 Mip machine is required to provide for a control rate of 250 hz.

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1 Introduction

Active force control capability is one of the most important characteristics of an intelligent robot. By actively controlling contact forces with the environment, a robot is able to perform highly sophisticated assembly operations which involve geometric constraints in the task space. Over the past years, much research has been done in this area and a few strategies for combined motion and force control emerged, such as the free joint method of Paul and Shimano, hybrid motion/force control strategy of Raibert and Craig, operational space formulation of Khatib, stiffness control of Salisbury and impedance control of Hogan. All these methods represent different levels of computational complexity and as such impose different computational constraints on the controller. Our attempt is to compare the above motion/force control strategies from the perspective of computation. By doing so, we hope to shed more light on one of the most important aspects of robot control, namely computational complexity.

2 The Need to Provide both Force and Motion Control

When working in a perfectly structured world we do not need sensing: a structured world in which the dimensions of all parts are within tolerance and in which careful planning has taken place to ensure that such parts can be assembled, a world in which everything is precisely located and everything functions as planned, a world in which all necessary jigs[19] have been designed and provided.

When any lack of structure occurs, however, we must rely on sensors. If something is misplaced, or if something will not fit, relying on a sensor-less, geometry controlled approach would be a disaster. Sensors have two roles, to monitor task execution and to establish the state of the world. Both these tasks require the use of a world model. Both tasks also require reasoning and planning. Establishing the state of the world requires a sensor strategy and the interpretation of sensor data in terms of the world model. Monitoring task execution also requires sensor strategies and interpretation of sensor readings in terms of the world model. Errors, when they occur, are detected by the interpretation of sensor data, once again in terms of

the world model. If this is to be done reliably a number of independent sensors are needed (sensors fail also). Once an error state is determined, appropriate recovery action must be planned. If a part is dropped on the floor, then it may be left, but if it is dropped inside a mechanism where it could prevent functioning, then it must either be retrieved or the mechanism replaced. Error recovery is not simple.

Of all the sensors that a robot might have, *force sensing* is the most fundamental. *Blind people function quite well in the world but people who have no kinesthetic feedback are totally helpless.* Consider the well structured world of manufacturing with a task fully under position control: the detection of any unexpected force is a clear indication that something has gone wrong. *Force sensing can provide this vital information.* In any situation where complete structure is absent, force sensing becomes primary in the sequencing of a task. Consider teleoperation where tasks have some structure[1].

The general-purpose manipulator may be used for moving objects, moving levers and knobs, assembling parts, and manipulating wrenches. In all these operations the manipulator must come into physical contact with the object before the desired force and movement can be made on it. A collision occurs when the manipulator makes this contact. General-purpose manipulation consists essentially of a series of collisions with unwanted forces, the application of wanted forces, and the application of desired motions. The collision forces should be low, and any other unwanted forces should also be small.

Three clear states may be identified:

1. Motion in free space.
2. Contact.
3. The exertion of a force.

This work of Goertz influenced the use of force sequencing in the manipulator control system WAVE[12] and later that of Inoue[3]. Two types of commands were included in a language WAVE describing a sequence of manipulator motions.

STOP terminate the current motion when a force equal to the argument is detected, also known as a “guarded move”[20].

FORCE during the next motion, the force in a given direction, is to be controlled to the value given as an argument. If the force is specified to be zero then the manipulator is “free” to move in the direction specified.

A further command allowed for a force to be applied by the manipulator, of course, the manipulator would have to be free in the direction

Taking a different approach in the “Force Vector Assembler Concept [7]” commanded manipulator Cartesian velocities could be modified by measured end-effector forces and moments

$$\mathbf{v} = \mathbf{v}_0 - [\mathbf{M}] \mathbf{f}$$

Off-diagonal elements of the matrix \mathbf{M} allowed for motion to be specified in directions orthogonal to an applied force. A curious side effect of this produced a switching phenomenon similar to that described above—a continuous control system with two states. *The end effector would trace along an edge until a corner was reached and then proceed to trace along the next edge.* Unfortunately it was not possible to continue in this fashion along the following edge. A similar “switching” phenomenon occurs in a special device for making chamfer-less insertions. *The pin is brought into the hole at an angle, on contact a linkage rotates the pin to align it with the hole axis whereupon insertion occurs.* These phenomena are, however, limited to only two states and do not generalize further. Recently this type of control has formed the basis of more complex insertion strategies [6] in the form of a “generalized damper” in which the force expected is proportional to the velocity error along some direction. Both of these strategies are limited to two-state systems. A task to insert a key into a lock, turn the lock 180 degrees, and then withdraw the key, cannot be characterized by such a continuous system. It is, however, simple to describe such a task in terms of force/displacement transitions and control mode switches such as used in WAVE [14].

The computational complexity in solving the reasoning and multiple real-time sensor processing are significant. We will, however, limit this study to the position and force control of a single manipulator working in

a dynamic environment in which one or more objects may be in relative motion.

3 Generalized and Operational Coordinates

Each component of a system has a unique coordinate system in which its state variables are most naturally expressed. An electric motor has its output shaft angle and shaft velocity as state variables; a camera reports observations in terms of scan line and position within the scan line; a robot manipulator is described in terms of its joint angles and their velocities; a milling machine is described in terms of its axes and their velocities. If various components are to work together there is a need for some form of common coordinate system which may be used directly to pass information between components. Information may be passed in terms of this common coordinate system or may be passed in terms of local coordinate systems defined in terms of this common coordinate system. The correct choice of coordinate systems is vital to the simplification of the description of spatial relationships.

Any orthogonal coordinate system may be used for the common coordinate system and although Cartesian coordinates are usually chosen other coordinate systems may be used cylindrical, spherical, etc. In certain situations one orthogonal coordinate system might have advantages over another, however, the transformation between them are all fairly equivalent and it is customary to employ Cartesian coordinates described by homogeneous transformations as this representation minimizes the computational cost of performing the transformations.

There is a computational cost involved in transforming between coordinate systems and it is usual in robotics to define local coordinate systems to reduce the number of transformation to one or two transformations in order to relate between components. The computation cost is of the order of 60 flops (floating point operations) but might double if re-normalization of the result is employed.

Transformations are provided between each device and some local Cartesian coordinate frame described by a homogeneous transformation. The cost of this transformation varies with the device, however, one of the most complex devices is the manipulator itself. In the case of manipulators it is

always possible to define the transformation between the generalized joint coordinates and a Cartesian coordinate frame located at its terminal link, for the PUMA manipulator this involves some 141 flops. The inverse relationship, between Cartesian terminal link coordinates and generalized joint coordinates, is not always possible. However, if certain kinematic restrictions are met [16] this is also possible; for the Puma this involves some 227 flops.

In practice then, sensor observations would be transformed by a non-linear sensor transformation into Cartesian sensor coordinates, these would then be transformed into base coordinates by a homogeneous transformation product. This might be followed by a second transformation into manipulator tool coordinates, representing a second homogeneous transformation and then finally into manipulator joint coordinates using the inverse kinematic transformation. This method results in absolute coordinates being available at all times.

An alternative approach, in the case of small changes to a reference position, is to use Jacobians representing the differential change between the initial coordinates and the final coordinates. Even if this is done in a number of steps: from the sensor to Cartesian coordinates, from the sensor Cartesian coordinates to the manipulator coordinates, and finally from manipulator coordinates to joint coordinates. Each of these transformation involves a minimum of 66 flops. This method also involves the updating of the Jacobians involving considerably more arithmetic operations.

It can be seen that both methods, absolute and differential transformation, are fairly equivalent and in practice the absolute method is usually employed.

4 The Description of Motion and its Computational Cost

Manipulator motion is possible in either joint coordinates or in Cartesian coordinates. In the former case the manipulator joints move along straight lines in joint space whereas in the latter the terminal link of the manipulator moves along straight lines in Cartesian space. Joint motion, while well defined, does not result in straight line motion in Cartesian coordinates.

However, joint coordinates represent the state variables of manipulators and they define the extremum constraints on motion, maximum speed, acceleration, motion limit, etc. and if time optimal motions are desired then joint motion is natural. In the terminal phases of many motions a well defined motion is needed and in this case Cartesian motion is more desirable; time optimization is not so important as is the simplicity of the description of the motion in space.

One of the first methods of coordinated control of manipulators was by Paul in 1972 [12]. The method involved control of the manipulator in joint coordinates, that is, each joint of the manipulator was driven at the same relative speed. Thus at mid-trajectory each joint was exactly half way between its initial position and the desired final position. If the motion end-point specification was given in Cartesian coordinates the inverse kinematics would be called to determine the end-point specification in joint coordinates [8]. This could be done before the manipulator was moved and thus the computational rate at which the inverse kinematics could be calculated was immaterial¹. Once the final and initial joint coordinates have been obtained their difference may be reduced to zero in some simple manner maintaining continuity of one or more derivatives (continuity of velocity and acceleration) [10]. A fifth order polynomial with time as independent variable will suffice for this purpose.

4.1 Joint Coordinate Motion

The motion from B to C may be defined in joint coordinates as a function of h by obtaining the joint coordinates corresponding to positions **B** and **C**, θ_B and θ_C , as:

$$\theta = r\theta_{BC} + \text{solve}(\mathbf{EXPR}_{i+1}(t))$$

¹The multiple solutions obtainable with a six-degree-of-freedom manipulator were initially thought to be a simple problem and simple algorithms such as picking the solution whose joint angles were closest to the current ones were often employed. It developed that the selection of the solution was of great importance. Its selection is complicated and is now normally just left to the programmer, suitable for robot level languages, but will become a problem when task level programming is attempted.

$$\begin{aligned}
&\text{where} \\
&\theta_{BC} = \text{solve}(\mathbf{B}) - \text{solve}(\mathbf{C}) \\
&r = 1 - h
\end{aligned}$$

The variable r changes from 1 to 0 as the motion is made. When $r = 1$ at the beginning of the motion $\theta = \theta_B$ the initial position. When $r = 0$ at the end of the motion $\theta = \text{solve}(\mathbf{EXPR}_{i+1})$, the desired final position. h is defined as a function of time to provide for continuity of motion. A fifth order polynomial is required. In addition there is a discontinuity in position and velocity between the two motion segments and a further fifth order polynomial is also required [11].

4.2 Orthogonal Coordinate Motion

If an orthogonal motion is desired from B to C then the position equation must be modified to include a drive transform $\mathbf{D}(r)$ [13] in **EXPR**. The drive transform represents a translation \mathbf{d} and rotation ψ about an axis \mathbf{e} in space proportional to r , $1 > r \geq 0$. When the argument r is zero, representing the end of the motion, $\mathbf{D}(r)$ reduces to an identity transform. The position of the drive transform in the equation determines the frame in which the rotation is defined. We can rewrite the previous motion equation with the drive transform included in the form

$$\mathbf{pi} : \mathbf{T}_n = \mathbf{L}_i \mathbf{D}(0) \mathbf{R}_i$$

Here \mathbf{L}_i represents the transform expression to the left of \mathbf{D} and \mathbf{R}_i represents the transform expression to the right. At the beginning of the motion from B to C position B is defined by equation the above equation. This position is also defined with respect to position C.

$$\mathbf{B} = \mathbf{L}_C(-t_{acc}) \mathbf{D}(1) \mathbf{R}_C(-t_{acc})$$

which we may solve for $\mathbf{D}(1)$

$$\mathbf{D}(1) = \mathbf{L}_C^{-1}(-t_{acc}) \mathbf{B} \mathbf{R}_C^{-1}(-t_{acc})$$

From $\mathbf{D}(1)$ we may obtain \mathbf{d} , \mathbf{e} , and ψ and the orthogonal motion from position B to position C may then be described by

$$\theta_n = \text{solve}(\mathbf{L}_C(t) \mathbf{D}(r) \mathbf{R}_C(t))$$

$$\begin{aligned} &\text{where} \\ &r = 1 - h \end{aligned}$$

as r varies from 1 to 0.

A problem with both schemes is picking the time for the motion. Once a time is picked a well controlled motion is obtainable however; like the configuration which was initially picked using some simple algorithm the picking of the time is extremely complicated. If the time is too small the the manipulator will not be able to track the specified motion. The time is dependent on the dynamics, drive systems, previous and subsequent motions. Although much research has been devoted to this problem it remains a formidable computational problem only to be undertaken if repeated motions are to be made. However, if repeated motions are to be made then far simpler techniques are available which use the actual manipulator and gradually decrease the time of motion segments until some criteria has been met. In practice a very conservative motion capability is assumed so that none of these problems surface, however, the manipulator runs at typically 30% to 50% of potential. This is a problem in factory automation but is not a problem in intelligent robotics when careful motions normally require that the manipulator move slowly in a very well controlled manner.

5 Control

The control of a robot is a complicated task. It requires task planning, trajectory generation, kinematic solution, implementation of control, dynamic evaluation and servoing. All these subtasks are associated with a certain amount of computation. Furthermore the nature of the subtask also determines the rate at which the computation should be carried out. It thus becomes necessary to classify computation into categories and determine the rate of computation for each category accordingly.

In this paper, we divide the computational task into the following categories. Kinematic computation and dynamic computation. The first category consists of the configuration dependent quantities, those parameters of the control which only depend on the position of the manipulator not on its velocity or acceleration. The dynamic category consists of the dynamic trajectory generation, control law computation and joint servoing. The computations in the dynamic category have to be carried out at the control

rate. However, the computations in the kinematic category need be carried out only at the rate of change in robot configuration. This rate is considerably slower than the sampling rate and so the distinction between these two categories allows the controller to have a two-layer structure. While all the dynamic computations are done in a real time process, the kinematic computations are executed in a slower background process.

The amount of computation for the control of a robot also depends on the robot type, our results are obtained for a PUMA260, which is fairly typical of modern robots. The forward and inverse kinematic solutions are obtained symbolically, and so is the Jacobian[9]. The calculation of the dynamics quantities is based on a method developed by Paul and Izaguirre [4]. The results are listed in Table 1.

In the following section, we shall compare seven force/motion control methods according to the computational loads in both the kinematic and dynamic categories. They are listed below.

- 1. Free Joint Method by Paul.**
- 2. Modified Free Joint Method by Shimano.**
- 3. Hybrid Control by Raibert and Craig.**
- 4. Modified Hybrid Control by Zhang.**
- 5. Operational Space Control by Khatib.**
- 6. Stiffness Control by Salisbury.**
- 7. Impedance Control by Hogan.**

For each method of control, a control diagram is drawn. To reflect the layered nature of control, a vertical line is drawn that separates the kinematic process from the dynamic one. To ease the burden of counting operations, all boxes and summation junctions are numbered. In general, all boxed quantities are either constants or can be computed at the kinematic rate. But the ones in the dynamic region have contributions to the dynamic computational load due to the multiplications and additions involved in computing the real-time quantities. Similarly, summation junctions in the

dynamic region contain dynamic computations and those in the kinematic region contain kinematic computations.

There is a box labeled G_i in every diagram. This is the trajectory generator. The $G1$ trajectory generator computes a joint trajectory based on a Cartesian end point specification which may be changing with respect to time. The $G2$ trajectory generator computes a Cartesian trajectory. $G3$ computes both the desired Cartesian position trajectory and the desired velocity trajectory. $G4$ computes the desired Cartesian position trajectory, the desired velocity trajectory and the desired acceleration trajectory. For the sake of comparison, the trajectory generator used in all these methods is the one by Paul [11]. It allows both joint and Cartesian motions to be generated. Smooth transition between trajectory segments is also provided by means of a matching polynomial. The worst computational load occurs when there is a transition into a Cartesian motion segment. Transition using a 7th order polynomial takes approximately 78 flops. In the case of the joint trajectory generation without a transition, it takes 250 flops since the computation also involves the inverse kinematics. The case of Cartesian trajectory generation, outside of the transition region, mainly involves the evaluation of the drive transform which takes 44 flops and two matrix multiplications which take 126 flops. The total number of flops is 181 including the computations of the motion parameter r . The following is a concise summary of the above discussion.

Trajectory Generator	Number of Flops
G1	328
G2	259
G3	283
G4	307

5.1 Free Joint Method

The Free Joint Method was an early method proposed by Paul [12]. The joint space is partitioned into two subspaces. In one subspace, the joints are position controlled and in the other subspace the joints are force servoed. The success of this method hinges on the ability to choose the right set of force servoed joints automatically. Using a simple algorithm to determine the free joints, the method is very elegant and the computation becomes

very simple and straight forward. Figure 1 is a diagram of the control method. Note that the trajectory generator is G1 and thus requires 328 flops. The following are the formulas used in the control.

$$F = F_{pos} + F_{force} + F_{dyn} \quad (1)$$

The total joint force, or torque, at each joint consists of three main components. There is the torque to provide position controlled, the torque at freed joints to achieve bias forces and contribution of the dynamic terms. F_{pos} and F have to be computed at the dynamic rate while F_{force} and F_{dyn} have to be computed at the kinematic rate. The amount of computation involved is 12 flops dynamic.

$$d\theta = \theta_d - \theta_o \quad (2)$$

This equation computes the joint error at the dynamic rate. The computation involved is 6 flops.

$$T_{pos} = K_p(\theta_o - \theta) + K_d(\dot{\theta}_o - \dot{\theta}) + K_i \int (\theta_o - \theta) dt \quad (3)$$

This equation uses a simple PID control law to compute the joint acceleration at the dynamic rate. Since joint errors are obtained already and the velocity errors can be calculated with 12 flops, the proportional term can be computed with 6 flops, derivative term with 6 flops and integral term with 18. In total it is 54 flops.

$$F_{pos} = D_{ij} T_{pos} \quad (4)$$

This equation computes the joint torque due to the acceleration obtained above. D_{ij} is a 6x6 inertia matrix. This represents a computational load of 66 flops at the dynamic rate. The inertia matrix will be computed in the last equation.

$$F_{force} = J^T F_d \quad (5)$$

This equation computes the bias torque and can be done at the kinematic rate. Both F_{force} and the Jacobian can be computed at the kinematic rate. Since all the sines and cosines of the joint angles are known from the inverse kinematics in the trajectory generator, the Jacobian takes only 65 flops and thus the whole equation takes 131 flops.

$$F_{dyn} = B_{(\theta)}[\dot{\theta}\dot{\theta}] + C_{(\theta)}[\dot{\theta}^2] + G_{(\theta)} \quad (6)$$

This equation represents the contributions of the Coriolis force, centrifugal force and the gravitational force. These quantities together with the joint inertia matrix D_{ij} can be calculated at the kinematic rate. With the method given by Paul and Izaguirre, it can be done with 710 flops.

Note that force feedback is open-loop. The manipulator joints are compensated for dynamics and friction. The resulting system is fast but approximate.

To summarize.

KINEMATIC COMPUTATION

Number of Flops: 841

DYNAMIC COMPUTATION

Number of Flops: 466

5.2 Modified Free Joint Method

This is a method Shimano developed based on the previous free joint method [15]. The difference in this method is that the Cartesian trajectory is modified continuously to compensate for the positional errors caused by force servoed joints. A recent attempt by the authors to compensate in the robot joint space is also successful. Our experience shows that if done correctly, the free joint based methods can be quite effective and simple. Figure 2 is a control diagram.

Note that the trajectory generator used is G2 and thus requires 259 flops at the dynamic rate. The following are the formulas used in the control.

$$F = F_{pos} + F_{force} + F_{dyn} \quad (7)$$

As before, this equation reflects the fact that the total joint torque can be divided into 3 components. There is the torque caused by position controlled joints, torque from force servoed joints and dynamic contributions. Again, the last two terms can be evaluated at the kinematic rate while the first at dynamic rate. It takes 12 flops dynamic.

$$d\theta = \theta_d - \theta_o \quad (8)$$

This again gives the joint errors. It takes 6 flops dynamic.

$$dx = Jd\theta \quad (9)$$

This equation calculates the Cartesian error caused by the joint errors. The Jacobian can be computed at the kinematic rate. So this means a kinematic computational load of 65 flops and a dynamic computational load of 66.

$$\delta = f(dx, S_c) \quad (10)$$

This equation forms the differential change matrix to be used in modifying the Cartesian trajectory of the robot. It does not need any computation.

$$x_d^m = x_d * \delta \quad (11)$$

This is the modification of the Cartesian trajectory. The maximum computational load is 6 flops.

$$\theta_d = \Lambda_{(x)}^{-1} \quad (12)$$

This equation is the inverse kinematics. It is transforming the modified Cartesian trajectory into the desired joint trajectory. It takes a total of 227 flops of dynamic computation.

$$T_{pos} = K_p(\theta_o - \theta) + K_d(\dot{\theta}_o - \dot{\theta}) + K_i \int (\theta_o - \theta) dt \quad (13)$$

This equation utilizes a PID control law to compute the joint acceleration. All the computation has to be carried out at the dynamic rate. As seen before, it takes 54 flops.

$$F_{pos} = D_{ij} T_{pos} \quad (14)$$

This equation gives the joint torque caused by the joint acceleration. It requires 66 flops.

$$F_{force} = (I - S_\theta) J^T F_d \quad (15)$$

This calculates the bias torque to be applied. Since the Jacobian is already computed. The worst case for this equation is 66 flops of kinematic computation.

$$F_{dyn} = B_{(\theta)}[\dot{\theta}\dot{\theta}] + C_{(\theta)}[\dot{\theta}^2] + G_{(\theta)} \quad (16)$$

This is the rest of the dynamics terms and can be similarly computed as we did in the previous method. It takes 710 flops at the kinematic rate.

To summarize.

KINEMATIC COMPUTATION

Number of Flops: 841

DYNAMIC COMPUTATION

Number of Flops: 696

5.3 Hybrid Motion and Force Control

This method also involves two basic loops one for position control and another for force control. The method was proposed by Raibert and Craig [17]. Instead of having some joints force servoed, all joints in this method are position controlled but no positional feedback is applied in force controlled directions. Figure 3 is a control diagram. The trajectory generator is G3 and so both position and velocity are generated. The following are the formulas associated with the control law.

$$F = F_{pos} + F_{force} + F_{dyn} \quad (17)$$

As before, the total joint torque can be divided into three parts. The first term has to be calculated dynamically while the third term is computed kinematically. The second term with the force feedback is also computed dynamically. It takes 12 flops for the addition of all the three terms at the dynamic rate.

$$F_{pos} = D_{ij}T_{pos}^j \quad (18)$$

This again represents the joint torque caused by joint acceleration. D_{ij} is the inertia matrix in joint space. T_{pos}^j is the joint acceleration. This computation has to be carried out dynamically and takes 66 flops.

$$T_{pos}^j = J^{-1}(I - S)T_{pos}^c \quad (19)$$

T_{pos}^c is the Cartesian acceleration and this formula is used to convert the Cartesian acceleration to joint acceleration. The inverse Jacobian matrix can be computed at the kinematic rate and it takes 103 flops. The dynamic load is 66 flops for the matrix-vector multiplication.

$$T_{pos}^c = k_p(x_d - \Lambda(\theta)) + k_I \int (x_d - \Lambda(\theta))dt + k_D(\dot{x}_d - J\dot{\theta}) \quad (20)$$

This equation applies a PID control law in the Cartesian space. The proportional and integral terms use direct kinematics and the derivative term uses the Jacobian. The Jacobian can be evaluated kinematically and takes

65 flops assuming that the sin and cos of joint angles will be obtained in the kinematics. But everything else has to be computed dynamically. Knowing that the forward kinematics takes 141 flops the proportional term requires 153 flops. The integral term requires 18 flops. The derivative term takes 78 flops. In total, it takes 261 flops of dynamic computation and 65 flops of kinematic computation.

$$F_{force} = J^T S F_d + J^T S k_{fd}(F_d - C_H * F) \quad (21)$$

Since Jacobian is already calculated in the last equation, the first term requires only 66 flops of kinematic computation. The second term takes 144 flops. In total, this equation takes 66 flops of kinematic computation and 150 flops of dynamic computation.

$$F_{dyn} = B_{(\theta)}[\dot{\theta}\dot{\theta}] + C_{(\theta)}[\dot{\theta}^2] + G_{(\theta)} \quad (22)$$

This term is basically the same as in the last two methods and it takes 710 flops of kinematic computation. Note that there is force feedback. The servo uses a PID control law in the joint space. Also note that the kinematics has to be evaluated every time in the servo.

In summary.

KINEMATIC COMPUTATION

Number of Flops: 944

DYNAMIC COMPUTATION

Number of Flops: 898

It is obvious that this method is computationally more expensive. That in part is due to the fact that errors are dealt with in the Cartesian space. In particular, joint angles have to be mapped into the Cartesian space using forward kinematics.

5.4 Modified Hybrid Control Formulation

The Modified Hybrid Control Formulation was aimed at reducing the computational load of the original hybrid method[21]. It shares many characteristics with the original hybrid control method, but the errors are dealt with in the joint space. Figure 4 is a control diagram of the method.

Note that the trajectory generator is G2. That implies a dynamic computational load of 259 flops. The following equations constitute the main body of formulation.

$$F = F_{pos} + F_{force} + F_{dyn} \quad (23)$$

As before, this equation represents 12 flops of dynamic computation.

$$d\theta = \theta - \theta_d \quad (24)$$

The joint error calculation takes 6 flops of dynamic computation.

$$x_d^m = x_d + SJd\theta \quad (25)$$

This is the equation that modifies the Cartesian trajectory. It takes 65 flops of kinematic computation to calculate the Jacobian assuming that sin and cos values of the joint angles are available from solving the inverse kinematics. Dynamic computation is 72 flops.

$$\theta_d = \Lambda_{(x_d^m)}^{-1} \quad (26)$$

This is the inverse kinematic function and it requires 227 flops of dynamic computation.

$$\theta_c = J^{-1}(I - S)Jd\theta \quad (27)$$

This equation calculates the joint compensation for compliance. Notice that $J^{-1}(I - S)J$ can be evaluated at the kinematic rate. Since $I - S$ is a diagonal selection matrix, $J^{-1}(I - S)J$ is really one matrix multiply. Therefore there are 499 flops of kinematic computation and 66 flops of dynamic computation. Among the 499 flops, the computation of J^{-1} takes 103 and $J^{-1}(I - s)J$ takes 396.

$$\theta_r = \theta_d + \theta_c \quad (28)$$

This represents the modification of the desired joint trajectory using the joint compensation θ_c . It takes 6 flops of dynamic computation.

$$F_{pos} = D_{ij}T_{pos} \quad (29)$$

This equation gives the joint torque due to joint acceleration T_{pos} . It requires 66 flops of dynamic computation.

$$T_{pos} = K_p(\theta_r - \theta) + K_d(\dot{\theta}_r - \dot{\theta}) + K_i \int (\theta_r - \theta) dt \quad (30)$$

This is the joint acceleration computation. As shown before, it takes a total of 66 flops of dynamic computation.

$$F_{force} = J^T S F_d \quad (31)$$

This is the bias torque computation. It can be done at the kinematic rate and takes 66 flops.

$$F_{dyn} = B_{(\theta)}[\dot{\theta}\dot{\theta}] + C_{(\theta)}[\dot{\theta}^2] + G_{(\theta)} \quad (32)$$

This combines the contributions of the Coriolis force, centrifugal force and the gravitational force. As seen before, it requires a kinematic computation of 710 flops.

In the formulation, it is assumed that there is no force feedback. x_d^m is the modified Cartesian setpoint. Note that servo is done in the joint space.

In summary.

KINAMETIC COMPUTATION

Number of Flops: 1340

DYNAMIC COMPUTATION

Number of Flops: 780

5.5 Operational Space Control

In this method Khatib [5], formulated the dynamic equation in the task or operational space. The motivation for doing this seems natural. A manipulator task is most simply described in operational space instead of the joint space. Why not then also perform the control in this space too? Within the framework of the Operational Space Formulation, a unified approach for controlling both force and position is derived. A control diagram is shown in Figure.5. Note that trajectory generator G4 is used and that

takes 307 flops of dynamic computation. The following are the formulas in the formulation.

$$F = \Lambda_x \ddot{x} + \mu_{(x,\dot{x})} + p(x) \quad (33)$$

This equation is the dynamics equation of the robot formulated in the operational space. Λ_x is the operational space inertia matrix and is crucial to the control of the robot.

$$\Gamma = A_{(\theta)} \ddot{\Theta} + B_{(\theta)} [\dot{\theta} \dot{\theta}] + C_{(\theta)} [\dot{\theta}^2] + G_{(\theta)} \quad (34)$$

This is the corresponding dynamics equation in the joint space. This is important because all the Cartesian coefficients of the dynamics equation are to be derived from the joint based coefficients.

$$F = J^T (F_{pos} + F_{force}) + F_{dyn} \quad (35)$$

Again, the total force is divided into 3 components. J can be computed at the kinematic rate and it takes 65 flops assuming that the sin and cos of the joints are known from the kinematics. Dynamic computation is 78 flops.

$$\Lambda_{(\theta)} = (J_{(\theta)}^{-1})^T A_{(\theta)} J_{(\theta)}^{-1} \quad (36)$$

In this equation, the operational inertia matrix is obtained. Kinematic computation consists of computing J^{-1} , $(J^{-1})^T A J^{-1}$. The first can be done with 103 flops and the latter with 792 flops.

$$F_{pos} = \Lambda_{(\theta)} \Omega F_{pos}^* \quad (37)$$

This equation gives the Cartesian force for position servo. It has 180 flops of kinematic computation and 66 flops of dynamic computation.

$$F_{pos}^* = K_d \ddot{x} - K_p (Kin_{(\theta)} - x_d) - K_v (J \dot{\theta} - \dot{x}_d) \quad (38)$$

This equation computes the acceleration in the operational space. It involves the forward kinematics and the Jacobian. The dynamic computation is 249 flops.

$$F_{force} = \tilde{\Omega} F_{force}^* + \Lambda_{(\theta)} \tilde{\Omega} F_s^* \quad (39)$$

This is the force due to force servo. It contains a operational force term and a velocity damping term. The amount of dynamic computation is 102 flops and that of kinematic computation is 36 flops.

$$F_{force}^* = F_d + K_f (F_d - F_{obs}) \quad (40)$$

This equation uses a simple proportional law to compute force and takes 84 flops of dynamic computation.

$$F_s^* = K_{vf}\dot{x} \quad (41)$$

This equation gives the velocity damping and takes 6 flops of dynamic computation.

$$F_{dyn} = \tilde{B}_{(\theta)}[\dot{\theta}\dot{\theta}] + \tilde{C}_{(\theta)}[\dot{\theta}^2] + G_{(\theta)} \quad (42)$$

$$J\dot{\theta} = H_{1(\theta)}[\dot{\theta}\dot{\theta}] + H_{2\theta}[\dot{\theta}^2] \quad (43)$$

$$\tilde{B}_{(\theta)} = B_{(\theta)} - J^T \Lambda H_1 \quad (44)$$

$$\tilde{C}_{(\theta)} = C_{(\theta)} - J^T \Lambda H_2 \quad (45)$$

This group of 4 equations provides the dynamic compensation for the operational space control. Assuming that they are done kinematically, the amount of kinematic computation is at least 2618 flops. We say at least because we assumed that H_1 and H_2 are available. Solving the above equations, we obtain the following overall equation:

$$\Gamma = J^T[\Lambda_{(\theta)}(\Omega F_m^* + \tilde{\Omega} F_s^*) + \tilde{\Omega} F_a^*] + \tilde{B}_{(\theta)}[\dot{\theta}\dot{\theta}] + \tilde{C}_{(\theta)}[\dot{\theta}^2] + G_{(\theta)} \quad (46)$$

Unfortunately the computational costs are increased due to the need to map the control into operational space.

KINEMATIC COMPUTATION

Number of Flops: 3794

DYNAMIC COMPUTATION

Number of Flops: 892

The large number of equations and the relative complexity of them in this category explains the large number of operations required. We assume that the joint space dynamic coefficients are computed using the method of Paul and Izaguirre and then transformed into the Cartesian space.

5.6 Stiffness Control

Salisbury recognized that by assigning different stiffnesses along different directions, the manipulator can be made to comply with the geometric

constraints of the task space [18]. It is simple and elegant. Figure. 6 is a diagram of control. Note that the trajectory generator is G1 which requires 328 flops of dynamic computation. The following formulas are used in the formulation.

$$d\theta = \theta_d - \theta \quad (47)$$

This equation gives the joint errors and thus takes 6 flops of dynamic computation.

$$T_{stiff} = J^T K J d\theta \quad (48)$$

This equation provides the joint torque produced by the assignment of variable stiffness to the joint. $J^T K J$ and J can be calculated kinematically in the background. It takes 467 flops of kinematic computation and 66 flops of dynamic computation. Of the 467 flops, 65 results from computing J and the rest from evaluating $J^T K J$.

$$T_d = J^T F_d \quad (49)$$

This is the bias torque and requires 66 flops for the matrix-vector product at the kinematic rate. Note that the Jacobian is already computed in the last equation.

$$T_c = T_{stiff} + T_d \quad (50)$$

This equation simply combines the two forces. It takes 6 flops of dynamic computation.

$$T_s = J^T F_s \quad (51)$$

This is the equation that calculates sensed joint torques based on the sensed Cartesian forces. This takes 66 flops of dynamic computation. Taking the dynamics into consideration, the overall control equation takes the following form:

$$T = T_c + K_1(T_s - T_c) + K_c(\dot{\theta}_d - \dot{\theta}) + Dyn \quad (52)$$

We have already dealt with the first term of the equation. The second term will take 12 flops of dynamic computation. The third term will take 24 flops of dynamic computation and the last term will as usual take 710 flops of kinematic computation.

This formulation is very efficient. There is no need for the inverse Jacobian and JKJ^T can be computed in the background together with the Jacobian and the dynamics.

In summary.

KINEMATIC COMPUTATION

Number of Flops: 1243

DYNAMIC COMPUTATION

Number of Flops: 520

5.7 Impedance Control

Many force control strategies become unstable when a rigid manipulator comes into contact with a rigid environment. To solve this problem, Hogan argues that the dynamic nature of interaction dictates that the impedance of the mechanical system be controlled instead of either force or position [2]. Figure 7 is a control diagram of the method.

The following are the formulas used in the control formulation.

$$\tau_{actuator} = J^T F_{tip} \quad (53)$$

$$J_{(\theta)}^T (F_{tip} - F_{external}) = A_{(\theta)} \ddot{\Theta} + C_{(\dot{\theta}, \theta)} \dot{\Theta} + G_{(\theta)} \quad (54)$$

$$(55)$$

The above equations give the dynamics equation of the robot when it is interacting with the environment.

$$\dot{X} = J \dot{\Theta} \quad (56)$$

$$\ddot{X} = J \ddot{\Theta} + \dot{J} \dot{\Theta} \quad (57)$$

$$(58)$$

These are the differential relationships between Cartesian and joint velocities and accelerations.

$$F_{external} = M \ddot{X} + B \dot{X} + K(X - X_0) \quad (59)$$

This is the impedance model assumed.

$$\begin{aligned} \tau_{actuator} = & AJ^{-1}M^{-1}[K(X_0 - Kin_{(\theta)}) - BJ\dot{\Theta}] + \\ & [C_{(\dot{\theta}, \theta)}\dot{\Theta} + G_{(\theta)} - AJ^{-1}\dot{J}\dot{\Theta}] + \\ & J^T[I - J^{-T}AJ^{-1}M^{-1}]F_{external} \end{aligned} \quad (60)$$

This is the overall control equation. Since many terms are combined in forming the overall equation, the computational load for each individual equation does not make much sense any more. To resolve this problem, the computational load is tabulated in Table 2. Note that Bi represents Box i in the control diagram while Si represents summation junction i. Note also that J , J^{-1} , $AJ^{-1}M^{-1}$ and AJ^{-1} are computed in B4

As can be seen from the above, a direct kinematic process is included in the inner loop. Though, the overall equation looks quite complicated, many of its complex terms depend only on configuration and thus can be evaluated in the background at a slower rate. We will assume that $AJ^{-1}M^{-1}$, $AJ^{-1}M^{-1}BJ$, $AJ^{-1}J$, $J^T[I - J^{-T}AJ^{-1}M^{-1}]$ and all dynamic terms are calculated in the background.

KINEMATIC COMPUTATION

Number of Flops: 2210

DYNAMIC COMPUTATION

Number of Flops: 700

6 Dynamics

Up until now, the dynamic compensation of all the methods discussed above was touched upon only lightly. From the computational point of view, the task of computing the dynamic coefficients is very time consuming. The robot system itself is a multi-input, multi-output, nonlinear and coupled system. Under certain circumstances, the dynamic equation can be simplified so as to make the computational task easier. But for good control under general conditions all the terms in the dynamic equation become necessary. It is important to note that all joint based dynamic coefficients can be computed at the kinematic rate since these quantities change at the rate of change in configuration.

New method for computing dynamics coefficients has greatly simplified the computation in solving for the dynamic coefficients[4]. The amount of computation is tabulated in column one of Table 1.

In the operational space formulation, the dynamic equation is formulated in the operational space. This poses two problems. The first one is

that all dynamic coefficients in the operational space can only be obtained by transforming the coefficients from joint space. This transformation is a heavy computational task. Secondly, these coefficients have to be updated at a rate faster than the kinematic one because they change rapidly as a function of the inverse Jacobian.

From the results obtained above, it is evident that dynamics computation dominates the computational load. We believe that direct joint torque sensing is a promising alternative. By sensing the joint output torque directly it is possible to eliminate the need for the dynamics computations.

7 Control Rates

The rate at which the set point must be evaluated is related to the natural frequencies of the manipulator. While this is a complicated subject a figure of ten times the lowest dominant frequency may be used and is readily understandable. For anthropomorphically sized manipulators natural frequencies are of the order of a few hertz and control frequencies are of the order of some tens of hertz. The Puma is run at 35 hertz, other commercial manipulators run at 83 hertz and at 200 hertz. The actual control of the joint is however a different matter. Electric motors have much higher natural frequencies, tens of hertz being typical. These may be controlled to provide stiff position controlled joints by controlling them at hundreds of hertz, the Puma joints are controlled at over 1000 hertz other manipulators use special purpose chips to perform the control at four kilohertz. This form of joint control may be viewed as a form of velocity servo and relegated to special purpose chips of analog devices. We are concerned with the position control of the manipulator, the regulator which specifies the velocities to this inner joint controller. We believe, we may set this rate at 250 hertz for an anthropomorphically sized manipulator in order to provide for smooth control. Increasing the rate beyond 250 hertz only provides for diminishing returns. Decreasing it tends to cause roughness in the control and eventually instability.

A second computation rate is also involved. This relates to the computation of parameters, such as the manipulator instantaneous inertia, Jacobians, gravity loading, etc. These parameters depend only on the position of the manipulator, not on its velocity. As the position of a manipulator

only changes slowly, these parameters need only be computed at a rate dependent on rate of change of configuration. If we estimate that these parameters should be re-computed every time the manipulator changes its configuration by 5° and we further assume a maximum slew rate of 90° per sec. then we must compute these parameters at a rate of 18 hertz. Let us assume, for our computational calculations, that this rate is 25 hertz, one tenth of the control rate.

If we use these control rates for the kinematic and dynamic rates we may evaluate the floating point computational rates for the preceding methods.

Method	Kinematic flops	Dynamic flops	Total flops
Free Joint Method by Paul	21,025	116,500	137,525
Free Joint Method by Shimano	21,025	174,000	195,025
Hybrid Control by Raibert and Craig	23,600	209,500	233,100
Modified Hybrid Control by Zhang	33,500	195,000	228,500
Operational Space Control by Khatib	94,850	223,000	317,850
Stiffness Control by Salisbury	31,075	130,000	161,075
Impedance Control by Hogan	55,250	175,000	230,250

From the calculation of floating point operations required at the kinematic rate and at the dynamic rate it can be seen that the dynamic computations dominate. Kinematic computations represent typically 20% of the computational load.

If, however, this division is not made but all computations are made at the dynamic rate of 250hz. then the computational complexities differ greatly as indicated in the following table. It should be noted that this is the manner in which the calculations were initially proposed respective authors.

Method	Kinematic & Dynamic flops at dynamic rate
Free Joint Method by Paul	326,750
Free Joint Method by Shimano	384,250
Hybrid Control by Raibert and Craig	445,500
Modified Hybrid Control by Zhang	530,000
Operational Space Control by Khatib	1,171,500
Stiffness Control by Salisbury	440,750
Impedance Control by Hogan	727,500

8 VAX Instruction to Floating Point Ratio

We have examined two functions in detail in order to obtain the ratio between floating point instructions and machine instructions for optimized "C" code running on the VAX. The two routines were matrix multiply times and direct kinematics for the Puma 560 manipulator jnt-to-tr. These routines make use of a number of trigonometric and mathematics functions listed below:

Function	Flops	Mips
sqrt	10	30
sin	8	18
cos	7	17
atan2	8	25

Other arc trigonometric functions involve a sqrt and call to atan2. Step-by-step execution of the times algorithm, with normalization, revealed 135 flops and 324 instructions executed giving a mips to flops ratio of 2.40. Step-by-step execution of the jnt-to-tr direct kinematics routine revealed 164 flops and 393 instructions executed to give a mips to flops ratio of, once again, 2.40.

These observed flop counts agree well with the count of arithmetic operations in each of the algorithms. It is a strange coincidence that both basic robotics functions yielded identical mips to flops ratios of 2.40. As these are basic routines the execution of which occupies a large fraction of the cpu cycles we are, I believe, justified in using them to estimate the mip requirements of a processor based on a count of arithmetic operation counts in the algorithms.

We might note here that the vax generates very efficient code for expressions of the form

```
a = b * c + e * d;
```

```
muld3 b, c, r0
muld3 e, d, r1
addd3 r0, r1, a
```

If floating point variables are used they must all be converted by moving them first into registers resulting in poorer code

```

cvtfd b, r0
cvtfd c, r1
muld2 r0, r1
cvtfd d, r0
cvtfd e, r2
muld2 r1, r2
cvtdf r2,a

```

Similar code to this would be required for the 86020 as its addressing modes require that one operand is always in a register. This represents a two-to-one increase in instruction fetches. It is also interesting to note that over half of the arithmetic operations in the matrix multiply routine are related to re-normalizing the result.

9 Computational Cost Summary

Making use of the floating point estimations of the previous section together with the instruction to floating point ratio of 2.3 determined in the previous section we may summarize the computational requirements of the surveyed methods as follows:

Method	Flops	Mips
Free Joint Method by Paul	137,525	316,308
Free Joint Method by Shimano	195,025	448,557
Hybrid Control by Raibert and Craig	233,100	536,130
Modified Hybrid Control by Zhang	228,500	525,550
Operational Space Control by Khatib	317,850	731,055
Stiffness Control by Salisbury	161,075	370,472
Impedance Control by Hogan	230,250	529,575

10 Discussion

To compare computational complexity of a control method by counting the number of operations performed is a difficult task. It is difficult to be precise not only because of the complexity of control but also its dependence on hardware such as tachometer and force sensor. We tried to remain true to the original methods as they were first proposed and implemented.

It should be kept in mind that computational load varies depending on the number of directions of force control. To simplify the analysis, we assumed worst case situation for each category. Another important thing to remember is that there are other factors other than the computational load that impose real time constraints such as information transfer. Perhaps even more important is the way in which the total computation is distributed among different computers. By taking advantage of the matrix structure of the formulation, a parallel matrix processor can greatly facilitate the computation.

Assuming that the controller is organized in the layered manner separating kinematic computations from dynamic computations one may observe an almost 50% reduction in computational complexity by employing joint space methods over operational space methods. A more overriding consideration in the selection of a method, however, relates to the inherent robustness of the joint space methods even though they require the mapping of a task into joint space. In the case of redundant manipulators, not considered here, joint space methods become mandatory as it is joint space that the redundancy of the manipulators is represented.

It is also interesting to note that differential methods involving Jacobians and their inverses require a great number of arithmetic operations in performing the transformations; compare the Hybrid Control method proposed by Raibert and Craig based on absolute transformations to the modified hybrid control method which is based on differential methods.

It should be further noted that these figures are conservative and that an allowance of up to 20% additional computations might be appropriate. It should be also noted that the peak computational rates might exceed these figures by up to 100%

Thus in summary we might estimate the following computational rates

Method	Flops	Mips
Free Joint Method by Paul	330,060	759,139
Free Joint Method by Shimano	468,060	1,076,536
Hybrid Control by Raibert and Craig	535,440	1,286,712
Modified Hybrid Control by Zhang	548,400	1,261,320
Operational Space Control by Khatib	762,840	1,754,532
Stiffness Control by Salisbury	386,580	889,132
Impedance Control by Hogan	552,600	1,270,980

Thus if joint space control methods are employed a 0.5 M flop, 1 Mips machine would be appropriate. If operational space methods are employed a 0.75 M flop, 1.5 Mips machine would be appropriate.

	Forward Kinematics	Inverse Kinematics	Jacobian & It's inverse	Coefficients of Dynamics
Flops	141	227	258	710

Table 1.

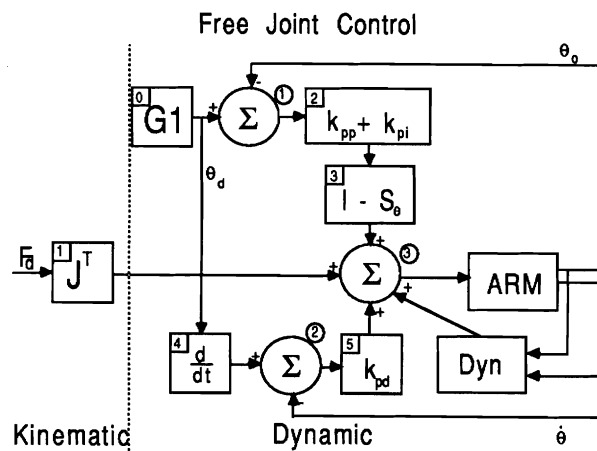


Figure 1.

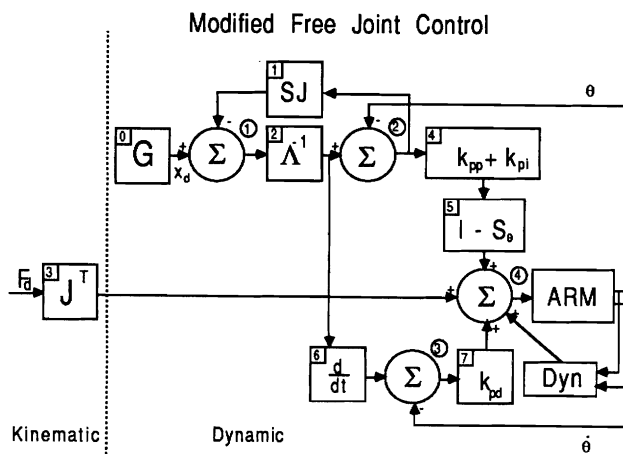
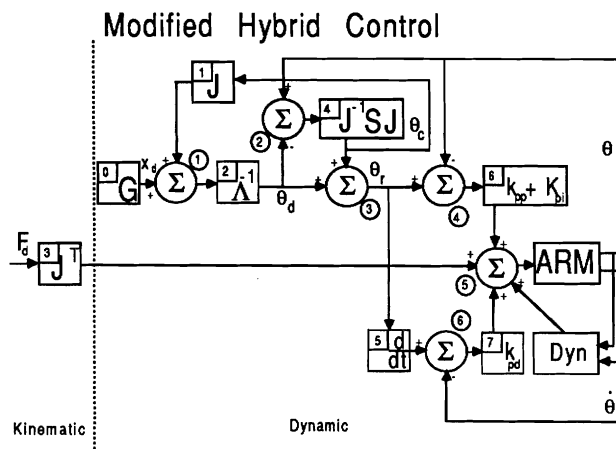
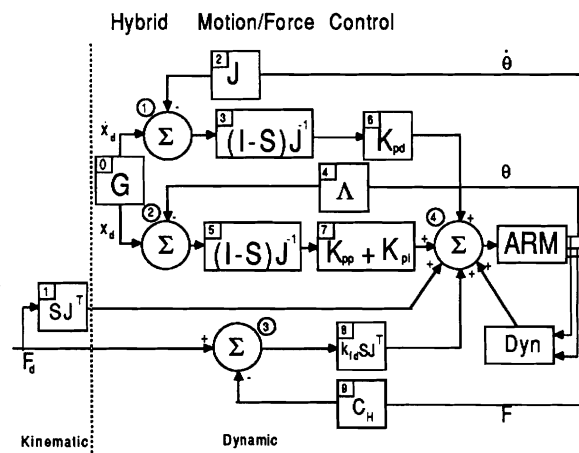
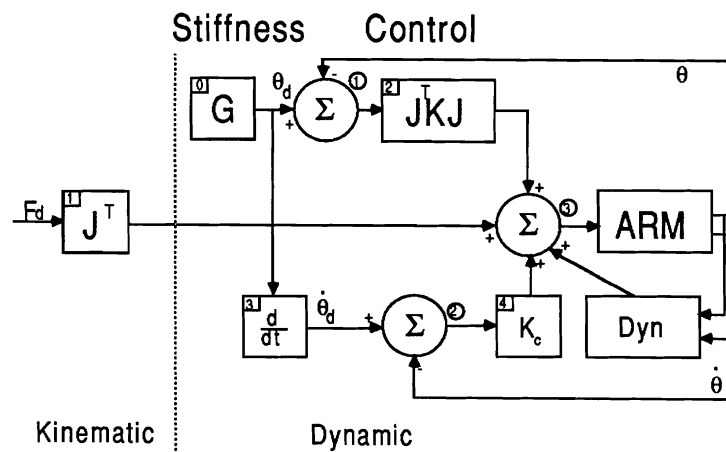
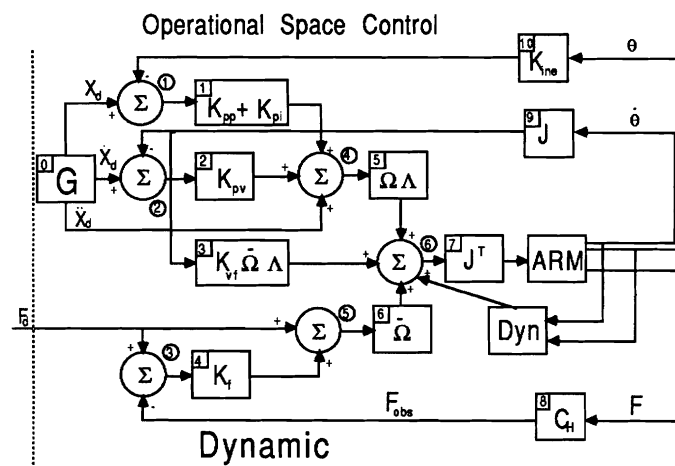


Figure 2.





[illegible]

Dynamic
Figure 7.

	B0	B1	B2	B3	B4
K	0	0	0	36	1086
D	259	141	6	66	66
	B5	B6	S1	S2	S3
K	0	468	0	0	0
D	66	66	6	6	12

Table 2

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